UCD: PHYSICS 9A LAB

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Read Me: About Labs in Physics 9

The Purpose of Labs

There are many reasons to include a mandatory lab component to the Physics 9-series. Among the benefits to a STEM education are:

- experiencing physical phenomena first-hand, to supplement the mathematically-abstract experience of lectures and problem-solving
- learning very broadly how one can go beyond what just intuitively seems right and actually *test an idea* by devising an experiment
- learning experimental skills, like minimizing errors and controlling for irrelevant factors
- learning data analysis skills, like using graphs and statistical examination
- learning to use uncertainty analysis to determine when a proposition is confirmed or refuted by the data

Some of the earliest labs in Physics 9A are somewhat less about physics, and more about developing some of these skills. At that point not a lot of physics has been learned yet, and these skills are needed throughout the 9-series.

Experiment Types

There are four basic varieties of experiments that will occur in these labs. Occasionally an experiment may have elements of more than one of these types.

- **Simple, repeatable, observations –** These are the most informal sorts of experiments. They typically do not involve a lot of mathematical modeling, and instead are focused on more general features. The most challenging aspect of these kinds of experiments is objectivity – the experimenter must come into them with an open mind, simply documenting what is observed without constructing elaborate explanations for what they are witnessing. One of the worst mistakes that can occur in these is to inadvertently "put your thumb on the scale" (introduce human error) because a certain result is expected. You should go to great lengths to avoid this critical error.
- **Confirmation of a Single Hypothesis** – A prediction is made regarding the outcome of a specific scenario. The result is never *exactly* what is predicted, but the amount of uncertainty measured and computed is used to determine if the experimental result is "close enough" to the predicted to result to be considered a confirmation.
- **Independent Confirmations –** Armed with the theoretical background to compute a physical quantity, the experimenter devises two separate, completely independent experiments to measure that value. Each experiment gives its own result and its own uncertainty range, and the goal is to check if the two experiments confirm the same number within these uncertainties.
- **Choose the Better Theory** – Two mathematical models are proposed to explain a single observed phenomenon. The experiment seeks to determine which of the two theories best describes the relationship between the variables present.

Typical Elements of Lab Meetings and Reports

Below is a list of common tasks performed in laboratory meetings, and items included in submitted lab reports:

- Short test runs of an apparatus are performed to "get a feel" for what is going to happen, and to assist in designing the setup in an optimal manner. These do not include actual data acquisition, and also should not be overused – some variation in results is expected, and variation is not an indication that the design needs to be tweaked indefinitely.
- Careful runs of the apparatus are performed, with multiple experimenters observing or playing a role in maintaining a smooth operation.
- Multiple runs are taken for each data point, to reduce statistical uncertainty. Sometimes the statistical uncertainty is computed and included in the analysis, other times just an average result of a few runs is used (because the statistical uncertainty only contributes a very small amount to the overall uncertainty). Doing this also helps weed-out weird anomalous runs where something unexpected and unnoticed happens (i.e. the removal of rogue data).
- Data tables are created (and included in the lab report). These include both raw data and values computed from that data, and are organized in a fashion that's easy for someone reading the lab report to review.
- Graphs (virtually always linearized – see here for more details) are produced, and best-fit curves (i.e. lines) are used to draw conclusions about the mathematical model used to explain the phenomenon tested in the experiment.
- Uncertainties of two types are computed:

- statistical – standard deviations of measurements with random errors introduced by the imperfect apparatus or by human involvement
  - estimated – educated guesses about how accurately one can expect a measuring device to function.
- Lab reports are written with contributions from all group members. The text does not need to be verbose or overly-details, but should get to the point and include most or all of the following points:
  - what you set out to test (explain the problem)
  - how you set up your apparatus to accomplish the test
  - what you expect to see (hypothesis)
  - your results (data tables, graphs, computations, general discussion, etc.)
  - checking to see if your results confirm the hypothesis to within the uncertainties (it is okay if this is not confirmed – staying agnostic about the final result is an important quality)
  - an accounting of the weaknesses in your apparatus or procedure, and suggestions for how these can be improved in future attempts

Organization of Reports

You are not required to follow a specific template for the format of your lab reports. However, it might be helpful to keep things organized in your head to follow something resembling this:

- **Goal** – Give a description of what you hope to accomplish or learn in this particular lab.
- **Hypothesis –** If the lab is one in which an hypothesis is tested, then expressing it explicitly is a good idea.
- **Procedure –** Give a details description of what you did in your experiment, from the preparation/calibration of the equipment, to the method of taking data. It is tempting here to sometimes give some numbers you recorded, but for the sake of organization it's a good idea to resist this. Also, while it is appropriate at times to give a short explanation of why you did something a certain way, this should be kept very brief, or this section will start treading heavily on the later section on analysis.
- **Data –** Display all the data you recorded, without including any discussion of what it means. This includes one-time measurements as well as tables. It's okay to include computed values (if, for example, every recorded number needs to be squared to be put into a graph), but save the main calculations toward a result for the next section.
- **Analysis and Conclusions** – This includes everything else:
  - physics that needs to be explained to get to your answer (free-body diagrams, algebra, etc.)
  - graphs and calculations of final results or uncertainties
  - a description of likely sources of error, and ways to improve the experiment (i.e. reducing errors/uncertainties)
  - final narrative that ties together the results of the experiment vis-a-vis the goal and/or hypothesis

A Final Word

These labs are intentionally not set up to be "cookbook" exercises. There will be some guiding questions to answer in the lab report, and some hints for how to proceed, but for the most part, the design of the experiment and the layout of the lab reports are up to you (your time is limited, so don't get too fancy with this). Keep in mind that you have two goals: The first is to convince yourself of the conclusion (i.e. perform a detail-oriented experiment), and the second is to write a clear lab report that conveys a convincing argument to the reader. Pro-tip for successful experimenters: Try to be more skeptical of your own work than the audience you seek to convince.

CHAPTER OVERVIEW

Lab 1: Uncertainty and Confirmation of Hypotheses

1.1: Background Material

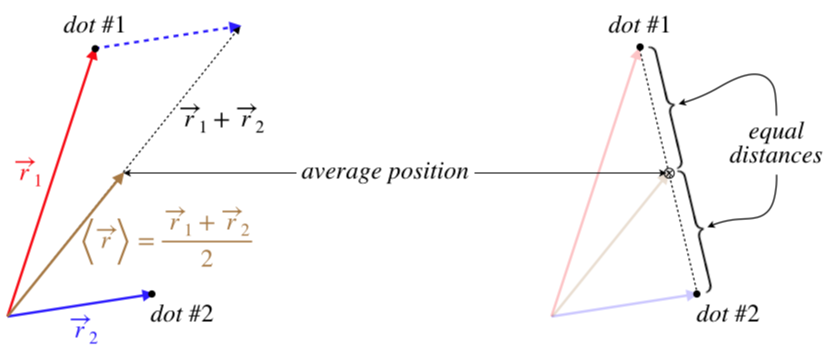
Average Position

In this lab we will be doing several trials that all produce dots on a piece of paper that measure the position of a marble as it strikes the floor. These dots can all be thought of as existing at the heads of position vectors, $\overrightarrow{r}_1$, $\overrightarrow{r}_2$, $\overrightarrow{r}_3$, and so on. As is typically the case for experiments, we will be interested in an average quantity over many trials – in this case the average position at which the marble lands. Finding an average vector is no different from finding an average number, namely:

$$\text{average position} = \left\langle \overrightarrow{r} \right\rangle = \frac{\overrightarrow{r}_1 + \overrightarrow{r}_2 + \dots + \overrightarrow{r}_n}{n} \tag{1.1.1}$$

We will not want to actually choose an origin and draw all these vectors, so it is helpful to come up with some way to find an average position directly from the positions of the dots. It isn't hard to show that the average position for two trials is just the point that is located halfway between the positions of the two trials.

Figure 1.1.1 – Average of Two Position Vectors



Finding the average position of more than two dots does not have quite as simple of a method, but we will use a trick to keep things from getting too complicated. Notice that if we have four dots, we can write the average position vector this way:

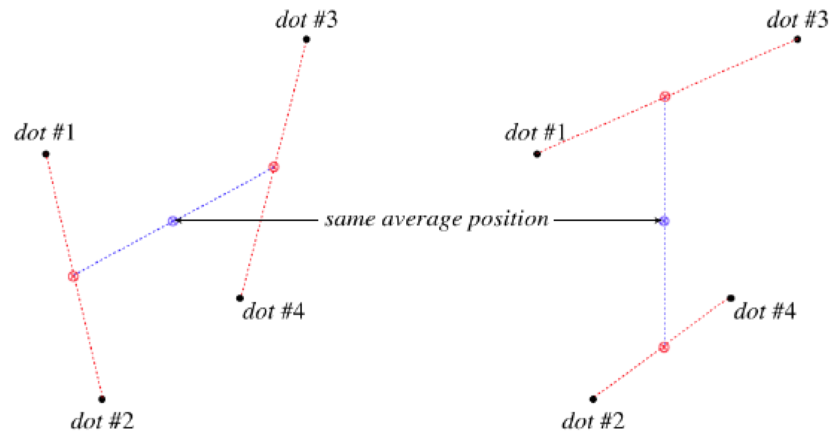
$$\left\langle \overrightarrow{r} \right\rangle = \frac{\overrightarrow{r}_1 + \overrightarrow{r}_2 + \overrightarrow{r}_3 + \overrightarrow{r}_4}{4} = \frac{\frac{\overrightarrow{r}_1 + \overrightarrow{r}_2}{2} + \frac{\overrightarrow{r}_3 + \overrightarrow{r}_4}{2}}{2} \tag{1.1.2}$$

This shows that we can get the average position of four dots by first finding the average positions of two pairs of dots, and then finding the average of those averages. This allows us to just use a ruler to locate the halfway points between pairs of dots to find the average position of all the dots. Notice that this procedure requires that we have some power-of-2 number of dots (2, 4, 8, 16, etc.). We could do it for a different number, but then we lose the "halfway between points" simplicity, and since we have control over the number of trials, we will stick with this method.

It should also be noted that it doesn't matter how we pair-off the points – in the end we end up with the same average position:

$$\left\langle \overrightarrow{r} \right\rangle = \frac{\frac{\overrightarrow{r}_1 + \overrightarrow{r}_2}{2} + \frac{\overrightarrow{r}_3 + \overrightarrow{r}_4}{2}}{2} = \frac{\frac{\overrightarrow{r}_1 + \overrightarrow{r}_3}{2} + \frac{\overrightarrow{r}_2 + \overrightarrow{r}_4}{2}}{2} \tag{1.1.3}$$

Figure 1.1.2 – Average Position of Four Dots Found Two Ways



Statistical Uncertainty

When we perform an experiment, we are interested in more than just the average value we obtain from many trials, we want to know to what extent this average can be trusted. That is, we want to know how *uncertain* we are that what have measured can be applied to any conclusions we might wish to draw. In the experiment we will perform, we will be "aiming" the marbles at a particular point on the paper, and the scatter of the dots is a result of uncertainty in our aim.

Whenever experimental runs have results that are scattered either because of human involvement or because the apparatus is not good at repeating a run very precisely, we determine the uncertainty *statistically*. This consists of computing what is called the *standard deviation*, which goes as follows:

- compute the average of all the data points

$$\langle x\rangle=\frac{x_1+x_2+\cdots+x_n}{n} \tag{1.1.4}$$

- compute how far each data point deviates from the average

$$\Delta x_1=x_1-\langle x\rangle\ ,\ \Delta x_2=x_2-\langle x\rangle\ ,\ \ldots \tag{1.1.5}$$

- square all the deviations from the average

$$\Delta x_1^2,\ \Delta x_2^2,\ \ldots \tag{1.1.6}$$

- average the square deviations

$$\left\langle\Delta x^2\right\rangle=\frac{\Delta x_1^2+\Delta x_2^2+\cdots+\Delta x_n^2}{n} \tag{1.1.7}$$

- compute the square root of the average

$$\sigma_x=\sqrt{\frac{\Delta x_1^2+\Delta x_2^2+\cdots+\Delta x_n^2}{n}} \tag{1.1.8}$$

This description of the computation of standard deviation makes it easy to remember, as we are just computing averages (first of the data points, then of the squares of the deviation of the data point values from the mean), but technically in these situations where we compute a mean from the actual data, there is a actually a slightly more accurate formula for standard deviation. It involves dividing the sum of the square deviations by $n-1$, rather than by n. We won't go into the technical details of why this is so, but it is important to note that the difference between these can become significant when n is quite small, as it often will be in our experiments. We will therefore henceforth use the so-called "unbiased" version of the standard deviation:

$$\sigma_x=\sqrt{\frac{\Delta x_1^2+\Delta x_2^2+\cdots+\Delta x_n^2}{n-1}} \tag{1.1.9}$$

The way this method of measuring uncertainty works for our present experiment should be clear: First use the method described above to determine the place on the paper that is the average landing point. Second, measure the distance from each dot to the average landing point. This is the "deviation from the mean" (Δx, measured in centimeters) of each data point. Then do the math from there.

Estimated Uncertainty

Another place where we introduce uncertainty in our results is in measurements. For example, if we are measuring a distance with a ruler, we would not expect our measurements to be accurate down to the micron ($\frac{1}{1000}$ millimeter), and we would estimate the uncertainty of these measurements to be more like in the range of perhaps a few millimeters. So in the experiment described above, our measurements of distances between dots and between the average landing points and dots introduces uncertainty into our results, because our measuring device does not measure these distances exactly. However, in this case we find that the tiny "few millimeter" estimated uncertainty of these distance measurements is insignificant compared to the statistical uncertainty associated with human aim (which is in the "few centimeter" range). We can therefore ignore the estimated uncertainty associated with ruler measurements for this experiment, as it contributes a negligible amount. Though both types of uncertainty typically occur in any experiment, it is usually true that only one type is the dominant version, allowing us to ignore the other. The simplest way to get a sense of this is to do a few repetitions of (what should be identical) runs, to get a sense of how much the results "scatter." While this experiment has this scatter greatly exceed the measurement uncertainty, more often than not, the reverse will be true. This is because we will use apparatuses that do a decent job of repeating runs.

So how do we make a decent estimate of a measurement uncertainty? Without going into the details that you may have encountered in a statistics class (like the nuances of the central limit theorem and the assumption of a normal distribution for our measurements), we will say that the range of uncertainty is such that we will expect that *roughly two-thirds of the data points will land within one standard deviation of the average*. While this works out automatically when we do the uncertainty statistically, we will use this as the standard for making our uncertainty estimates for measurements as well. That is, estimate the uncertainty of a measurement such that you would expect the true value of the measurement to lie within the uncertainty range of your recorded measurement roughly two-thirds of the time.

A Good Example to Keep in Mind

If you find the notions of statistical and estimated uncertainties confusing, here is a good model to keep in mind for them. Suppose you perform an experiment that involves measuring both a distance between two well-defined points, and a time interval between two events. So for example, a bouncing marble has pretty well-defined landing points, and the times between the landings is a time interval. The separation of the two points involves using a ruler or tape measure, and you can look at the markings on the measuring device to get an idea of the uncertainty in that measurement. This is an estimated uncertainty. The time interval is different – the device that launched the marble may not be consistent, but more importantly, if a human being is pressing a stopwatch when they see the marble land, then the uncertainty in this measurement is more amenable to statistical calculation – measure the time interval for several "identical" cases many times and compute the standard deviation.

1.2: Activities

Equipment

- $8\frac{1}{2}\times 11$ sheets of paper with two dots
- a ruler
- a compass for drawing circles (not for telling which way is north)
- a steel marble
- carbon paper
- wood plank landing area
- nail target

The General Idea

Humans are not able to aim precisely. If someone aims at a specific pinpoint target, the results of their attempts to hit the target will produce a scatter pattern around the target. If there are two targets, and the human aims at one of them, it may or may not be possible to determine from the scatter pattern which target was the goal, depending upon the proximity of the two targets and the amount of spread of the scatter pattern.

In this lab, we will create these conditions in the following way:

1. We are provided an $8\frac{1}{2}\times 11$ piece of paper with two dots (targets) on it. Taping this paper to the cardboard landing area and inserting the nail into one of the dots to define the intended target gives us a region to record runs.
2. Placing the carbon paper on top of the white paper gives us a means for recording the landing points of a steel marble dropped by a human aiming for the nail.
3. After a number of drops, a scatter pattern is created on the white paper.
4. After calculating the uncertainty in the scatter pattern, the spread from the average landing point can be computed mathematically, and then clearly delineated using the compass.
5. The "spread circle" should immediately show whether the intended target can be determined, and if so, which one it was.

In an attempt to show how this procedure works for various degrees of uncertainty in the scatter pattern, you will do **two** separate experiments (use separate pieces of white paper for each) – one where the marble is dropped from a position above the head of the dropper, and one where the marble is dropped from waist-height. *Important: It is possible for a human to hone their aim and improve their results with repeated trials, but we want every drop to be independent, so you should make sure that the dropper moves out of position after every drop, and starts fresh each time, giving them no way to make minute adjustments from the previous drop.*

Data Analysis

[*As this is your first 9-series lab, much more guidance will be given regarding the methodology than is typical. Future labs will have similar sorts of steps for data analysis, but will not be so spelled-out for you.*]

For each of your two runs, do the following:

1. Use the "average of averages" method outlined in Background Material to determine the average landing position of the marble. Multiple colors of ink will come in handy, to help you keep straight all the dots on the paper.
2. Compute the standard deviation of the position from the average landing position, using the ruler to measure how far each data point is from the average. Creating a table like the one shown below will be helpful. Also, rounding the measurements of Δx to the nearest half-centimeter and using two significant figures for Δx^2 should be plenty of precision.

dot	Δx	Δx^2
1		
2		
3		
4		
5		
6		
7		
8		

3. Use the compass and the ruler to draw a circle (probably best to use pencil) centered at the average landing position, with a radius equal to the uncertainty (standard deviation).

Hypothesis

In any other experiment, developing an hypothesis comes before the data collection and analysis. In this exercise we have placed it later, because the experiment doesn't test any actual physical principles, but has rather just been contrived to illustrate the concept of uncertainty. Whenever performing an experiment, the hypothesis outlines the expected results. In this experiment, since we are aiming at a specific point on the paper, the hypothesis is as simple as, "The person is dropping the marble on the target point on the paper." While no individual drop actually hits this target point, the hypothesis states what would happen if all of the uncertainty could be removed (i.e. if the person had perfect aim).

So how do we use our data to *confirm* the hypothesis? The short answer is that we check to see if the expected result lands within the uncertainty range of the experimental result (i.e. the average). In terms of what we have done here, the hypothesis is confirmed if the target point lies within the circle we have drawn around the average landing point.

But not so fast. The person may have actually been aiming at any number of points besides the target point – anywhere inside the circle, in fact. So it turns out that this hypothesis is too broad to be useful. A better hypothesis would be one that involves a *comparison*. This is why we have created two prospective targets, only one of which is the actual one, which we will call "Target A." Now we can form a more specific hypothesis: "Given that the person is aiming at one of the two targets, the target they are aiming at is A." Not all hypotheses can be boiled-down to two possibilities, but this is a nicely illustrative example. There are several possibilities here:

- ***only target A lies within the circle, confirming the hypothesis*** – It is important to understand that even with this confirmation, it doesn't prove beyond all doubt that the hypothesis is correct. It only confirms it to within our agreed-upon level of certainty.
- ***only target B lies within the circle, refuting the hypothesis*** – This would indicate that, to within uncertainty, the person was actually aiming at the other target.
- ***neither target lies within the circle*** – This result should lead us to reevaluate our starting point, where it was given that one of the two points was the target. Either that assumption was incorrect, or some mistakes were made in the experimental procedure or data analysis, or there was some unseen source of systematic error (e.g. a steady wind that blowing the marble horizontally during its journey).
- ***both targets lie within the circle*** – There are two possibilities for this result. First, it can be "fixed" by adding more trials, which will have the effect of moving the average landing point closer to the actual target (assuming no systematic errors), and farther from the alternative target, such that the latter then lands outside the uncertainty range. The second possibility is that the two targets are simply too close to each other for the degree of uncertainty we have. In this case, we say that the experiment "doesn't provide sufficient resolution" to confirm or refute the hypothesis.

Lab Report

Craft a lab report for these activities and analysis, making sure to include every contributing group member's name on the front page. You are ***strongly encouraged*** to refer back to the Read Me as you do this, to make sure that you are not leaving out anything important. You should also feel free to get feedback from your lab TA whenever you find that your group is at an impasse.

Every member of the group must upload a separate digital copy of the report to their lab assignment in Canvas *prior to leaving the lab classroom*. These reports are not to be written outside the lab setting.

CHAPTER OVERVIEW

Lab 2: Graphical Methods of Data Analysis

2.1: Background Material

Graphical Methods

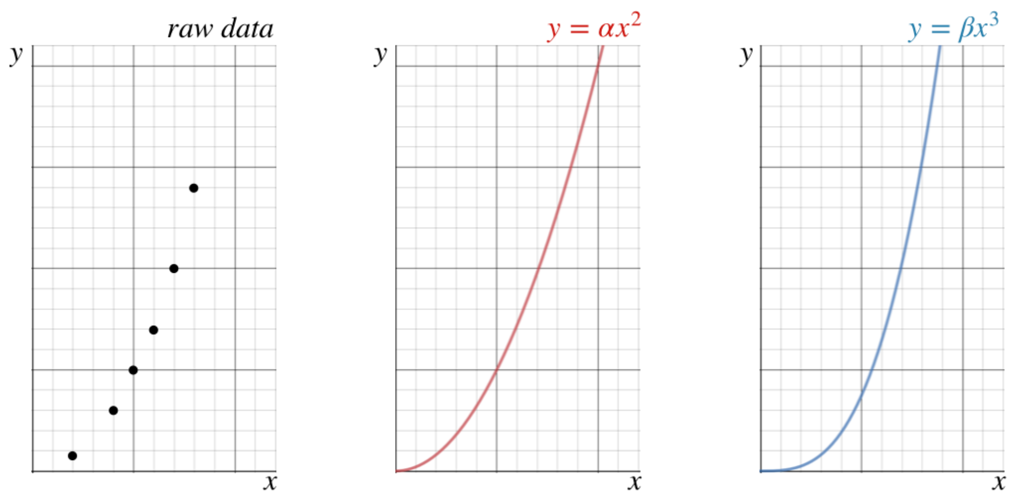
Very often our experiments are intended explore the mathematical relation between two quantities. Such experiments test an hypothesis that posits a certain functional relationship. For example, suppose we wanted to test the theory that objects dropped from rest fall a distance that is proportional to the square of the time elapsed after being released:

$$\text{distance fallen} = \Delta y \propto \Delta t^2 \tag{2.1.1}$$

How does one test such a proposition? Naturally lots of trials are required, where the time of descent and distance fallen are both measured. Multiple trials are needed for two elements of such an experiment. First, as we have already seen, we need to do several runs for fixed values of Δy and Δt in order to determine the uncertainties of our measurements. But we also need to do trials at a variety of values of Δy and Δt, so that we can test the functional dependence. We can never perform enough experiments to prove the relation beyond a doubt. As we saw in the previous lab, hypotheses that are framed as one conclusion against the entire universe of alternatives all suffer from this shortcoming, and it is generally better to do a direct comparison of two specific possibilities (in the previous lab, this consisted of framing the hypothesis in terms of aiming at target A or target B). So rather than use our data to confirm a single mathematical relation, we would use it to determine the relative merits of two competing mathematical relations.

There is a very powerful method for evaluating an hypothesis of this kind using the data acquired from all these trials. This method consists of plotting the data on a graph, and then checking to see which of the perspective formulas produces a graph that most closely fits the data (this is called a *best-fit curve*). There is software that does this for us, but rather than throwing this task into a black box, we get a better understanding if we do this "by hand," at least for awhile. When we plot the data points, we will undoubtedly notice that they follow some sort of curve, but it is not always obvious to the naked eye what function best fits those points. Consider the data points shown in the graph below, and two curves that we think may potentially express the correct functional dependence.

Figure 2.1.1 – Data Points and Two Prospective Curves



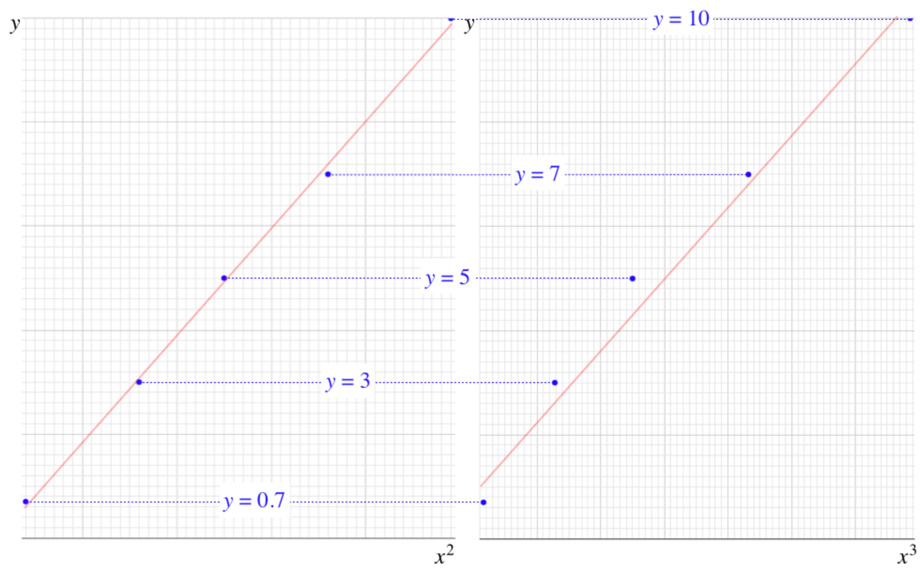
It certainly isn't clear from looking at the data alone which of the two prospective functions best fits it. If we superimpose the data points with the curves, we get a sense that perhaps the quadratic fits better than the cubic, but given the uncertainties in the measurements, it is by no means certain. What is more, creating these prospective curves is tricky business, since we are only testing power-dependence, which means we don't know what the values of α and β are. We have to keep tweaking these parameters until the curves are the best they can be – a very tedious task.

The main problem is that we humans are not particularly good at judging curvature of an array of points, and this can get even worse for functions more complicated than the two shown above. We are, however, pretty good at evaluating straight lines. It is therefore useful to change the graphs above to straight lines by plotting the y value versus the *prospective powers of* x. That is, make two plots of the data like the one on the left of the figure above, but plot y vs. x^2 for one graph, and y vs. x^3 for the other. Then take a straight-edge and see how well these data points can be aligned along it for the two cases. Whichever set of points more closely approximates a line is the one that reflects the functional dependence better.

Using the data in the figure above with every grid line equal to one unit, we can create a table, and plot the points on a grid for each of the two prospective functional dependences. In this particular case, the y-vs-x^2 plot displays the decidedly more linear form, while the y-vs-x^3 plot is quite obviously convex in shape. In other words, it is easier to fit a straight line to the y-vs-x^2 plot than it is to fit it to the y-vs-x^3. We therefore conclude that between these two choices, the dependence of y on x is quadratic rather than cubic.

Figure 2.1.2 – Creating Prospective Linear Plots

y	x	x^2	x^3
0.7	2	4	8
3	4	16	64
5	5	25	125
7	6	36	216
10	7	49	343



[As it has been expressed here, this is not a particularly quantitative way of determining which of the prospective functions is correct, but there is certainly a way to make it so. This basically consists of computing the aggregate of how far the data points deviate from the best-fit line. This gives a measure of how well the curve fits – called the R-value of that curve that varies from +1 to –1. The closer the absolute value of the R-value comes to 1, the better the curve fits the data. We won't go so far as to calculate R-values in this class, but you will likely run across it in another some other experimental science or statistics class.]

Some Final Comments

We get an added bonus by creating these linear plots. Note that the *slope* of the linear plot is the unknown constant of proportionality for the power law. We can find this constant by drawing our best-fit line, then selecting two points on the line and computing $\frac{\Delta y}{\Delta x}$. There are two important things to keep in mind while doing this. First, you are *using the line* to determine the slope, not two actual data points. So the two points used in the slope calculation must lie on the best-fit line. Second, in order to get as accurate a measurement as possible for the slope of the line, it is best to choose two points on the line that are as far apart on the graph as possible – if you choose two points that are close together, then a small absolute error in the reading of the x and y coordinates turns into a large percentage error in the ratio. It's also possible to derive information from the y intercept of the best-fit line. This will obviously give an additive constant, which, if it is not supposed to be part of the physics, can reveal a systematic error (e.g. every measurement of one of the variables was off by the same amount).

Note that if we have only two data points, then literally any curve can be made to fit, which means we get no information about functional form from only two data points. While two points are sufficient to determine the slope of a line, they are insufficient to determine the curvature (second derivative) of a non-line. If there are three points, then the curvature of a parabola that fits these points can be determined, but a cubic function can also be perfectly fit to those three points. The result is that as the power of the prospective curve grows, more data points are required to distinguish prospective functions. Of course it is always better to have more data points, but at a minimum, to distinguish between power laws with powers n and $n+1$, at least $n+2$ data points are needed.

It's also useful to note that the curvature of a graph is more apparent when the points are spread out. That is, a parabola can look like a straight line when points that are close together are plotted. Note that in the two graphs above, the horizontal axes are scaled so that the two most distant data points are at opposite ends of the graph.

2.2: Activities

Equipment

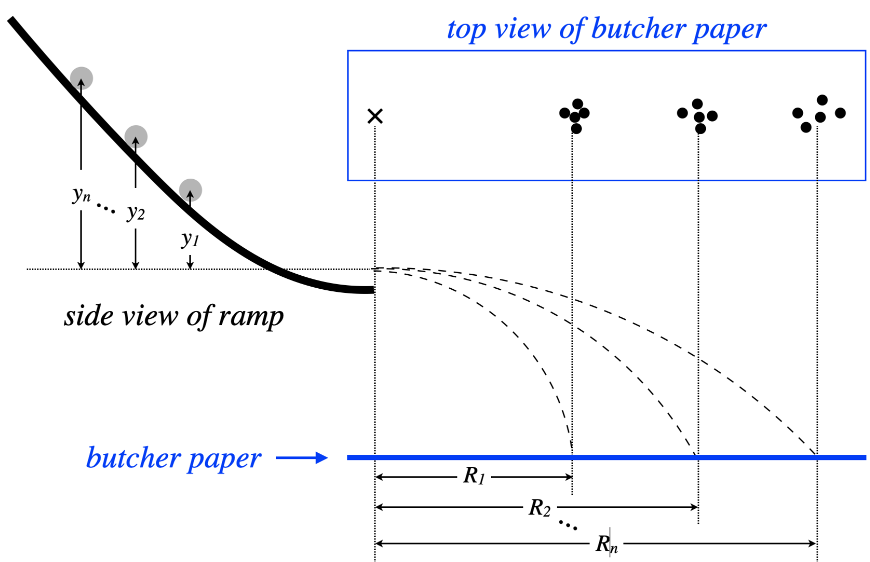
- butcher paper
- masking tape
- launch ramp
- a steel marble
- carbon paper
- meter stick
- plumb bob

The General Idea

Consider the somewhat contrived story...

A bitter controversy has recently broken out between the residents of a new housing development in the foothills and the Town Council over the safety of a number of large rocks perched on the slope of a hill that ends with a cliff, down to a lake, on the opposite side of which is the housing development. At the heart of the dispute is the relationship between the height above the edge of the cliff at which the rocks are balanced (y) and the distance, horizontally from the base of the cliff, to which the rocks will range (R) should they roll down the hill and fly off the cliff. Neither party is convinced by fancy physics calculations, so they both hired engineering firms to conduct modeled experiments to come to a conclusion.

Figure 2.1.1 – Engineers' Experimental Model



One group of engineers concluded that y and R are related by:

$$y \propto R \tag{2.2.1}$$

A second engineering firm concluded that y and R are related by:

$$y \propto R^2 \tag{2.2.2}$$

Further calculations reveal that if the trajectories obey the linear relation, then some of the rocks starting higher on the hill will fly over the lake and land within the housing development, but if the quadratic relation holds, then even the highest rocks on the hill will land in the lake, leaving the housing development undamaged.

Your Task: Set up the same experiment performed by the two engineering firms, and use the graphical technique discussed in the Background Material to draw a conclusion about which of the two relationships given above is the correct one.

Some Things to Think About

As you launch into this experiment, here are a few basic considerations to help you accomplish your goal:

- You are trying to decide between two different functions that may be difficult to distinguish from each other unless one is smart about taking data. One important bit of advice in this regard is in the final paragraph of the Background Material. It mentions the scaling of the graphs, but how will you *perform your experiment* to also help in this regard?
- One of the pieces of equipment is a plumb bob. This device is used to connect two points along a vertical line. How is this useful for this experiment?
- Humans make all sorts of errors when running experiments. In this case, one might record the wrong starting height, or accidentally give the marble a small push. How will you protect against the effect of such errors?
- The engineer's model assumes that the rolling marbles leave the cliff *horizontally*.
- All the experimental runs are performed on the same piece of paper. How bad would it be if the position of this paper is accidentally changed between runs?
- As is often the case, the keys to a successful experiment are planning (for which there are hints above), and a well-organized, orderly table of data and computed values.

[*As promised in the previous lab, from this point on in Physics 9 labs, you will be given only basic guidance (such as the few tips above). Setting up the means by which you take data and writing the report will be up to your group.*]

Graphing

For this lab and future labs that involve graphs, you are free to do these however you wish – you can graph the data by hand or use software. One tool you might find useful is this online graphing calculator. If you click the "+" button in the upper-left corner and selecting "table", you can enter your data into a table and the points will be plotted. Then in the upper-right corner you can click the "share your graph" icon, which will allow you to print it (which you can do on the lab printer) or save as a document. For this lab, we are only looking for the data that looks linear; we are not interested in the actual straight line that best fits the data.

Lab Report

Craft a lab report for these activities and analysis, making sure to include every contributing group member's name on the front page. You are ***strongly encouraged*** to refer back to the Read Me as you do this, to make sure that you are not leaving out anything important. You should also feel free to get feedback from your lab TA whenever you find that your group requires clarification or is at an impasse.

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CHAPTER OVERVIEW

Lab 3: Examining Air Resistance

3.1: Background Material

Text References

- free-body diagrams
- Newton's 2nd law
- air resistance

Improving Time Measurements

In many labs throughout the 9-series, we will need to measure the time interval between two events. Starting and stopping timers is rife with human error. To see the problem, consider what we have to do in this lab. We will be measuring the time it takes an object to fall a known distance. For some of these drops, the time span will be less than one half of a second. This means that if an error as little as one-tenth of a second is made, then the measurement is off by more than 20%. So how do we fix this problem?

The answer to this rests in our pockets. With a smartphone, we can make a decent-quality video recording of the fall of the dropped object. This video can be slowed to frame-by-frame, to determine the moment at which the drop and landing occurred. How do we measure these moments? When making the video, place a running stopwatch (another smartphone, or a laptop, if larger numbers are needed) in the frame. No need to start or stop it at the exact moment of the drop/landing, just pause the video at the appropriate frames after the recording and read the two times off. In this manner, the time of an event can typically be measured with an accuracy range smaller than ±0.03s.

Terminal Velocity and Mass

As discussed in the text reference on air resistance, a special case arises when an object's falling speed is fast enough that the drag force equals the weight of the falling object. With these oppositely-directed forces equal in magnitude, we have:

$$F_{drag} = mg \tag{3.1.1}$$

Since the drag force depends upon the speed of the object, this equation implicitly results in a relationship between the terminal velocity and the mass of the object (there are other factors involved as well, but we will focus on mass and hold the others constant). Most scientific references of the relationship between drag force and velocity indicate that it typically varies between linear ($m \propto v$) and quadratic ($m \propto v^2$). What decides between these two is complicated, but it can be experimentally determined.

3.2: Activities

Equipment

- coffee filters
- two-meter stick
- timing device

The General Idea

This lab consists of two separate parts. The first involves testing a proposed mathematical model of the motion of an object in free-fall while experiencing air resistance, and the second is an examination of the effect of the object's mass on its free-fall velocity after it has been falling awhile.

Part 1

It is well-known that an object dropped from rest near the Earth's surface with negligible air resistance will fall a distance as a function of time given by this equation:

$$y=\frac{1}{2}gt^2 \tag{3.2.1}$$

This lab is all about motion in the presence of air resistance that is *not* negligible. Some things are intuitively clear about what happens when air resistance plays a role. First, there is a force (called "drag") that acts in the opposite direction of the motion of the object relative to the air. And second, in the case of a falling object, this force opposes the gravity force, which causes the object to accelerate at a rate *less than* g.

Given that we know that the acceleration of a falling object is less than g, it leads us to consider the possibility that the correct equation to describe distance fallen as a function of time when air resistance is present looks like:

$$y=\frac{1}{2}kt^2, \tag{3.2.2}$$

where k is a constant that is less than g, which depends upon the details of the falling object (e.g. feathers have lower k values than stones).

We can check this experimentally by dropping an object to the ground from many different heights and measuring the time elapsed in each case, to see if this functional dependence applies. As with the previous lab, you are not required to fit a line to the data; you only need to determine *if* the data does seem to form a line. Again, you are encouraged to use the online graphing calculator to plot your points.

Part 2

As the falling object speeds up, the drag force increases, and when it gets large enough that it happens to equal the gravity force, then the net force (and therefore the acceleration) will be zero. An object falling through the air with no acceleration maintains a constant velocity (commonly referred to as "terminal velocity"). We know from experience that different objects have different terminal velocities, and the main factor that comes to mind is mass. If we hold all other factors fixed and just change the mass, we can determine whether the drag force (for terminal velocity) is roughly proportional to v or v^2.

Some Things to Think About

Though it might seem straightforward, there is a lot going on in this experiment, and a lot to think about, both in terms of physics and experimental methods. Here are some pointers to help you on your way...

Part 1

- As with any experiment, we don't want to change any variables that we aren't testing. The coffee filters you are working with have very specific aerodynamic qualities, namely: how wide they spread, and whether their pleats remain intact. As you are taking data, be very gentle with these (and make repairs to it as needed) to keep the aerodynamic variables held as constant as possible.
- With the video/timer method of taking data described in the Background Material, you will find that your measurements of time-of-fall are pretty consistent. Knowing this makes for a nice time-saver. Normally you would want to do several runs at a

single height, take mean of the time measurements, compute the standard deviation, etc. But to save time, it is easier to do just *two* runs at the same height. If they come out very close to each other (within a couple hundredths of a second), take the average and move on to another height (no need for uncertainty analysis in this lab). If they are very different, do a third run and throw out the rogue measurement.

- To get a good sense of the y-vs-t curve, you will need a wide range of values. You should do at least 5 different heights, with two of them quite short (less than $50cm$, and two of them quite high (more than $150cm$).
- We get a "free" data point. In a time of zero seconds, the object falls zero meters. So the origin can be used as a data point – and the most reliable one at that!
- As this is an experiment to prove/disprove a functional dependence, we need to do this graphically. You may want to review the Background Material for Lab #2 as a reminder of the danger of drawing a conclusion about the function that defines a curved graph, and how to avoid this pitfall.
- As always, a data table with measured and important computed quantities is essential.

Part 2

- If you wish to approximate the terminal velocity of the object from the data in part 1, do you need the entire graph of data points to do this, or can you do so more simply? It may help to think about how velocity (and particularly terminal velocity) can be extracted from the y-vs-t graph.
- We have discussed two possibilities for the relationship between the drag force and terminal velocity. Hypothesize one of them. Test your speculation by changing the mass of the falling object from part 1, and take the minimum number of measurements you'll need. It's best not to make a significant increase in the mass (no more than double the original), or the object may not actually reach its terminal velocity.
- Be careful that changing the mass doesn't also change some other factor that plays a role in air resistance – we must only change one variable at a time!

Lab Report

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CHAPTER OVERVIEW

Lab 4: Static Friction

4.1: Background Material

Text References

- static friction
- pulleys
- inclined planes

Estimated Uncertainty

In Lab #1, we noted the importance of measuring and accounting for uncertainty in experimental results. In that case, we calculated uncertainty from a range of measurements of a single quantity (the landing positions of a marble relative to its average landing point). We called this a statistical uncertainty, which we said arises cases where there is randomness in repeating the process (often due to human involvement). In this lab, the uncertainty will not come from this source, but rather will come from the limitations of our measuring devices (e.g. we can't measure distances to within microns using a meter stick). Rather than taking several runs, we will *estimate* uncertainties that are introduced into the experiment in this way, and we will use them to appropriately define the limitations of our experimental results.

Percentage Uncertainty

Usually the uncertainty in a quantity has little meaning out of context. For example, if we are measuring the speed of an object, and compute the uncertainty in that speed to be $\pm 1.0 \frac{cm}{s}$, then the level of our knowledge about this object's speed is quite impressive if we are talking about a bullet fired from a gun, and it is not so impressive if we are talking about a strolling tortoise. It is therefore useful to define *percentage uncertainty*, which is the ratio of the *absolute uncertainty* (whether it is statistical or estimated) and the quantity in question:

$$\text{percentage uncertainty in measured quantity } x = e_x = \frac{\sigma_x}{x} \tag{4.1.1}$$

Uncertainty Propagation

In this lab, we will not be measuring the physical quantity in question directly. Instead, we will measure multiple quantities, and put them together mathematically to compute what we are looking for. This poses us with a new problem – there will be uncertainties in all of our measurements, so how do we use these to determine the uncertainty of their combination? We will virtually never be adding or subtracting quantities, so we really only have to worry about how we deal multiplying/dividing uncertain numbers and raising uncertain numbers to powers.

Without going into the mathematical details behind it, we will simply state that whenever two uncertain quantities are multiplied or divided, the percentage uncertainty in the product or ratio is found by computing the *quadrature* (a fancy word that means "treat them like the legs of a right triangle aand use the Pythagorean theorem") of their individual percentage uncertainties:

$$\left.\begin{array}{c} z = x \cdot y \\ or \\ z = \dfrac{x}{y} \end{array}\right\} \quad \Rightarrow \quad e_z = \sqrt{e_x^2 + e_y^2} \tag{4.1.2}$$

If the quantity we are calculating instead involves a power, then the rule is a little different. For example, if we have $z = x^2$, it is *not* correct to simply use the quadrature formula above with x replacing the y (this would result in an uncertainty for z that is $\sqrt{2}$ times the uncertainty of x). Instead, the rule is to *multiply the percentage uncertainty of the measured quantity by the power*:

$$z = x^n \quad \Rightarrow \quad e_z = n \cdot e_x \tag{4.1.3}$$

Weakest Link Rule

Given that this is a physics lab, we don't want to be spending all of our time doing uncertainty calculations, so we will employ a shortcut that will reduce our workload somewhat. For just about every case where we will need to propagate uncertainty associated with multiple measurements, one of the measurements will have a significantly larger percentage uncertainty than the others. Say for example that we make measurements of two quantities that are multiplied, where one of the percentage uncertainties is 1% and the other is 4%. Putting these together gives:

$$\left.\begin{array}{l} z = x \cdot y \\ e_x = 1\% \\ e_y = 4\% \end{array}\right\} \quad \Rightarrow \quad e_z = \sqrt{(1\%)^2 + (4\%)^2} = \sqrt{17}\% = 4.1\% \tag{4.1.4}$$

As you can see, the resulting percentage uncertainty differs very little from the larger of the two percentage uncertainties. We will therefore use the shortcut we call the *weakest link rule*, which consists of simply finding the component that has the largest percentage uncertainty, and using that as the total uncertainty, without ever computing the quadature. Note that we still need to include the power rule shown above, however. For example, if the quantity we are computing looks like $z = xy^2$ and x has a 4% uncertainty, while the uncertainty of y is 3%, the square of y in the computation of z makes its 6% contribution the weakest link.

Comparing Two Uncertain Results

We know how to determine whether an experimental result agrees with an "exact" (theoretical) number – we just check to see if the experimental result lands within the absolute uncertainty of the exact value. But something we will do in several labs is perform two different experiments to find the same value (this is most common when we don't actually have a theoretical number to check against). We will want to know if these two experiments confirm each other's results, but how do we do this, when both provide inexact answers? The answer to this (again, without going into details) is to compare the two results (which are of course both averages of the data), and determine whether the amount that they differ lies within a certain range, which is defined by the quadrature of the *absolute* uncertainties generated for each of the results:

$$range = \sqrt{\sigma_1^2 + \sigma_2^2} \tag{4.1.5}$$

Let's look at a quick example. One experiment yields a (unitless) result of $7.40 \pm 3\%$, while the result of the other experiment is $7.63 \pm 2\%$ (perhaps these percentages were found for each experiment using the weakest link method). Do these two experiments agree to within uncertainty? Well, if we add 3% to the first result, we get 7.622, so the second result does not land within the uncertainty of the first. Conversely, the first result does not lie within the uncertainty of the second result. But the real question is whether their difference of 0.23 lands within the range:

$$\left.\begin{array}{l} 0.03 \cdot 7.40 = 0.222 \\ 0.02 \cdot 7.63 = 0.1526 \end{array}\right\} \quad range = \sqrt{0.222^2 + 0.1526^2} = 0.269 > 0.23 \tag{4.1.6}$$

So these experimental results are consistent with each other to within uncertainty. Notice that if one of the results is "exact," (whether it is a theoretical answer or an experiment with very small errors) its uncertainty is zero, and the range is just the uncertainty of the other experiment.

4.2: Activities

Equipment

- wood plank
- sliding block with string
- pulley apparatus
- hanging weights
- adjustable-height platform
- triple beam balance
- meter stick

The General Idea

In this lab, we are going to explore static friction. Static friction is a bit trickier than kinetic friction, inasmuch as it is not a fixed quantity – it depends upon the other forces applied to the object. But there is one aspect of it that is fixed – the maximum value that it can acquire for a given pair of surfaces in contact. This maximum is characterized by the coefficient of friction, which is what we will be measuring in this lab. We will do this by measuring the minimum force we can apply to the object parallel to the surfaces that will make the object accelerate.

To make sure that the *type* of parallel force is not important, and that the contact force between the surfaces also does not affect the coefficient of static friction, we will do two different experiments. One will use tension to pull the block along a horizontal surface (so gravity does not contribute to the parallel force, and the magnitude of the contact force equals the entire weight of the block), and the other will involve an inclined plane with no string pulling (so that only a component of gravity is the parallel force, and only a fraction of the block's weight equals the magnitude of the contact force). We will then compare the results obtained for the coefficient of static friction in the two cases, incorporating the uncertainties of the two experiments to determine if the results are "close enough" to each other to declare our result to be valid.

Some Things to Think About

Effects of static friction can be pretty touchy to measure accurately. In addition, this "touchiness" makes the process of estimating uncertainty of measurements troublesome, so here are a few things to keep in mind:

- The string needs to be parallel to the sliding surfaces. Also, swinging weights are to be avoided, because they provide more tension than if they are stationary.
- The cradle for the hanging weights is not weightless (but you have a scale!).
- If the block is not in precisely the same position on the plank for every trial, then the two surfaces in contact are not exactly the same – some parts of the plank may be smoother than others.
- Somewhat strangely, the *history* of the block on the plane seems to play a role. If it has been resting in the same place for awhile, the ability to make it slide may be significantly different from if it was just placed there. Also, the temperature of the surfaces (warmer if they have just recently been rubbed) may also play a role. [I told you it was touchy!]. Try to come up with a way to keep these variables under control.
- Even with all of the above controls in place, you will find that repeated runs under the same conditions (as "same" as you can make them) yield different results. These varied results will be the best source of your estimated experimental uncertainty for the weight hung from the string (in experiment #1) and the height of the ramp (in experiment #2) – better than using the smallest unit you can measure. For example, even though you can adjust the hanging weight by as little as one gram, you will find that one gram is not actually the degree of uncertainty you are working with. A similar issue occurs with measuring the height of the ramp at which the block slides. You don't have to compute the uncertainties statistically (though you can if you wish), but you do need to repeat the procedure to get enough of a sense of the variation of results to make a good estimate.
- Be sure to carefully follow the procedure outlined in the Background Material with respect to using the weakest link rule and comparing the two results.

Lab Report

Craft a lab report for these activities and analysis, making sure to include every contributing group member's name on the front page. You are ***strongly encouraged*** to refer back to the Read Me as you do this, to make sure that you are not leaving out anything

important. You should also feel free to get feedback from your lab TA whenever you find that your group requires clarification or is at an impasse.

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CHAPTER OVERVIEW

Lab 5: Energy Forms

5.1: Background Material

Text References

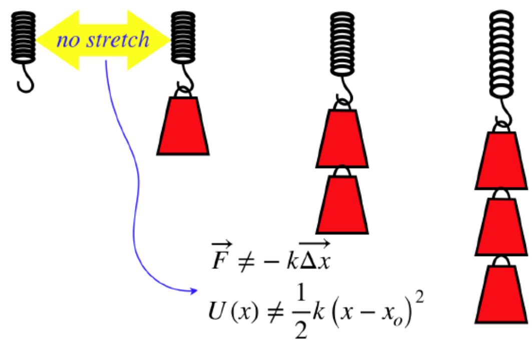
- work done by a general force
- mechanical energy conservation

Non-Ideal Springs

We found the potential energy function for a spring by computing the work done by that spring. This assumes that the spring is "ideal," which means that it perfectly obeys Hooke's law. It turns out that many real springs don't closely approximate this behavior. The springs used in this lab are no exception.

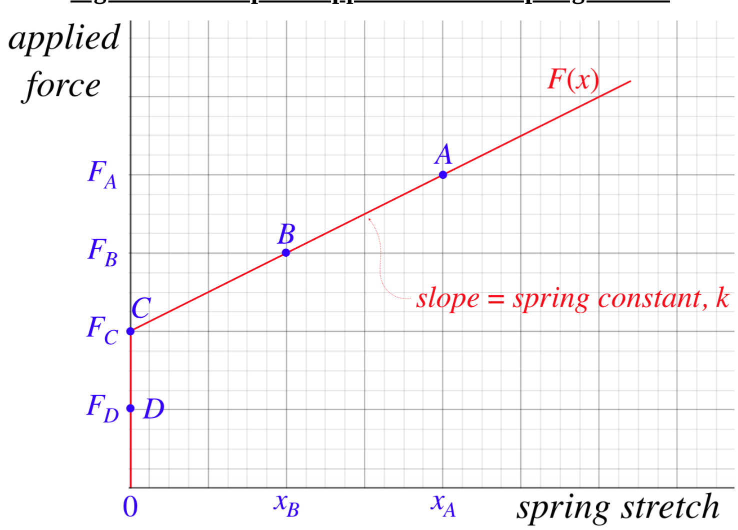
The spring used in this lab pulls its coils tightly together. That is, the pull of the spring is not zero when the spring is at its minimum length – the pull is balanced by the repulsive normal force between the coils that are in contact. If we hang a small weight from these springs, the coils don't separate. With no change in coil separation, the spring force doesn't change – the contact forces between them just get a bit smaller. Eventually, when we add sufficient weight, the coils do separate, causing the spring force to increase (and of course the contact force between coils vanishes, as they are no longer in contact). But the force exerted on the spring does not exhibit Hooke's law, which means that the potential energy stored in the spring can not be computed in the usual way.

Figure 5.1.1 Coil Behavior for Our Non-Ideal Spring



This doesn't mean we can't do anything with these springs, because we can still measure the displacement for various forces, which means that we can still compute the work done on the spring by stretching it. Of course, we need to know how the force changes as a *function* of the displacement to do the work integral – we can't simply multiply the force by the displacement.

Figure 5.1.2 Graph of Applied Force vs. Spring Stretch



The graph above shows how the spring behaves when certain forces are applied to it (in our experiment, we will do this by hanging weights). Imagine applying force F_A first, and noting the amount that the spring stretches x_A. When we reduce the force to F_B, naturally the spring stretch decreases (to x_B). As long as the coils don't touch each other, this follows a linear relationship, as we would expect for any spring. But when we reduce the force to the point where the coils are in contact (F_C), then every applied force from there down to zero produces the same stretch – zero.

When we store potential energy in a spring, we do this by doing work on the spring, and for a perfect spring, this work happened to equal the potential energy function $\frac{1}{2}kx^2$ that we are so familiar with. But this is not such a spring, so to determine the potential energy stored in the spring, we must do a new calculation of the work done on it, using the function $F(x)$ that we will determine experimentally.

Gravitational Potential Energy of Extended Objects

When an object changes heights, its gravitational potential energy changes, which is proportional to its change in height. When the object is not a point mass (i.e. it has extension in space), different parts of the object can be at different heights. How do we measure the change in potential energy, when there are so many points to choose from? What happens if the object rotates as it rises? The answer (which we will proved later in the course) is that this potential energy is computed using the change in height of the object's *center of mass*. Keeping this in mind for the spring, which actually changes length during its journey will be useful.

5.2: Activities

Equipment

- spring
- paper clips
- clamped post
- 2-meter stick
- hanging weights

The General Idea

The physical system we will be examining is that of a spring that is threaded over a vertical post. The spring is closed at the top, so that the top is prevented from going lower than the top of the post. The bottom of the spring is then pulled downward, stretching it, and is released, after which the spring leaps upward. Our goal is to test energy conservation by measuring the energy stored in the spring before it is released, and compare it to the gravitational potential energy the spring gains at its peak height (at both of these stages, the kinetic energy is zero).

When confronted with the details of this experiment, a theorist works on the problem, and declares that because the coils collide when the spring returns to its original shape, the mechanical energy lost from this "inelastic collision" (a topic we will cover soon) is substantial. A simple model reveals that in fact the amount of mechanical energy that is lost during this process is $25\% \pm 4\%$ (i.e. between 21% and 29%). We now seek to test this model's prediction with an experiment.

Some Things to Think About

A significant amount of thought needs to go into the physics behind this experiment, and much of this is addressed in the Background Material. Here are some pointers about those issues:

- The spring is not ideal, so you cannot compute the potential energy stored within it using $\frac{1}{2}kx^2$. This means that the stored potential energy has to be computed using the work done on the spring to bring it to a given stretch, and this work can be computed graphically after taking some data (which should be tabulated, as usual) on what force is required to stretch the spring various amounts. Small changes in the best-fit line of this graph can possibly lead to some fairly significant differences in the final result, so you will want many data points for your graph, to narrow the range of best-fit lines that work. Spread out the data points as much as possible, from very small to large stretches. **But do not over-stretch the spring – you will not need to hang more than 300 grams.**
- It is challenging to measure the heights to which the fast-moving spring rises, so you should again consider recording video on a smart phone to slow things down and get a better view.
- The change in gravitational potential energy of the spring is determined by the distance that its *center of mass* rises. Some care must be taken to make sure you get this value correct, given that the spring is stretched at its lowest point and not stretched at its highest point.
- You will not need to estimate uncertainties for the measurements of this experiment, because these come out to be insignificant compared to the uncertainty range built into the theoretical model.
- As with any experiment that has values difficult to measure (like the height the spring attains), it is useful to do the same run more than once, to make sure you did not experience a "glitch" with a single trial (you are only required to do the full analysis for a single spring launch, however).
- Unlike previous labs in which we merely plotted data points, this time we actually need to *use* the best-fit line that these data produce. If you use the usual online graphing calculator to plot these data points, then you can add a second formula with the equation for a line, $y = mx + b$. Create sliders for m and b and adjust these values until the line fits the data points way you think it should (in future labs, we'll have the computer do this for you). You can then print this as usual for your lab report, but what is nice is that you *have the actual equation* for your best fit line, and you can work with that for your final calculations, rather than refer back to the graph.

Lab Report

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CHAPTER OVERVIEW

Lab 6: Momentum and Impulse

6.1: Background Material

Text References

- impulse and momentum
- perfectly inelastic collisions
- elastic collisions

Force and Motion Sensors

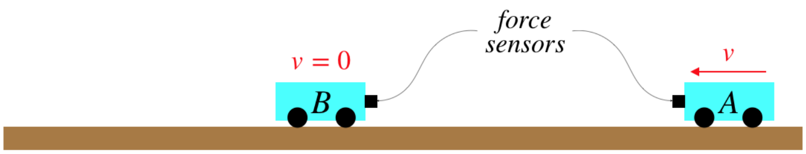
The equipment used in this lab includes two sensing devices that take data in real time. One of these is a force sensor (located on one end of the cart), which measures force exerted in Newtons, and the other a motion sensor (activated by the turning of the wheels of the cart), which measures velocity in meters per second.

Both of these sensors send their readings via Bluetooth to a laptop at regular intervals. Upon receiving this information, the computer plots the values versus time on graphs, the details of which we will use for our analysis. Forces are recorded as positive values when they push on the sensor, and negative values when they pull on it. Motion detected by the motion sensors is recorded as a positive value when the object is moving in the direction where the force sensor is in front.

The experiment involves collisions of nearly-frictionless rolling carts. As we are interested in the forces exerted on each cart as a function of time, we don't want the collision to be between two hard surfaces, or the period of time over which the forces act will be too brief to measure, even at the impressive sampling rate of our force sensors. We have therefore engineered the two types of collisions we will study so that the force of the collision occurs at a "leisurely" pace.

For simplicity, all of the cases we will study will involve a stationary target cart, but the conclusions of the experiment will be independent of this choice.

Figure 6.1.1 – Anatomy of the Collisions



We therefore will end up with four graphs plotted at the same time – a force and velocity for each cart. The information we extract from these plots will allow us to draw conclusions about impulse, momentum conservation, and kinetic energy conservation.

6.2: Activities

Equipment

- carts & track
- laptop
- Pasco sensor devices
- cart linking accessories
- weights
- electronic weight scale

The General Idea

We have seen in the textbook that the impulse-momentum theorem is a repackaging of Newton's 2nd law:

$$\vec F = m\vec a = m\frac{d\vec v}{dt} = \frac{d\left(m\vec v\right)}{dt} = \frac{d\vec p}{dt} \quad \Rightarrow \quad \int\limits_a^b \vec F dt = \vec p_b - \vec p_a \tag{6.2.1}$$

We will use fancy sensing equipment to confirm this (as well as the 3rd law) by directly measuring all the physical quantities involved in different collisions. Specifically, you will make these impulse/momentum and 3rd law tests for three separate scenarios, *all of them involving a* ***stationary*** *target cart*:

- magnetic repulsion collision with carts of equal masses
- magnetic repulsion collision with carts of unequal masses
- link-up collision with carts of whatever masses you choose

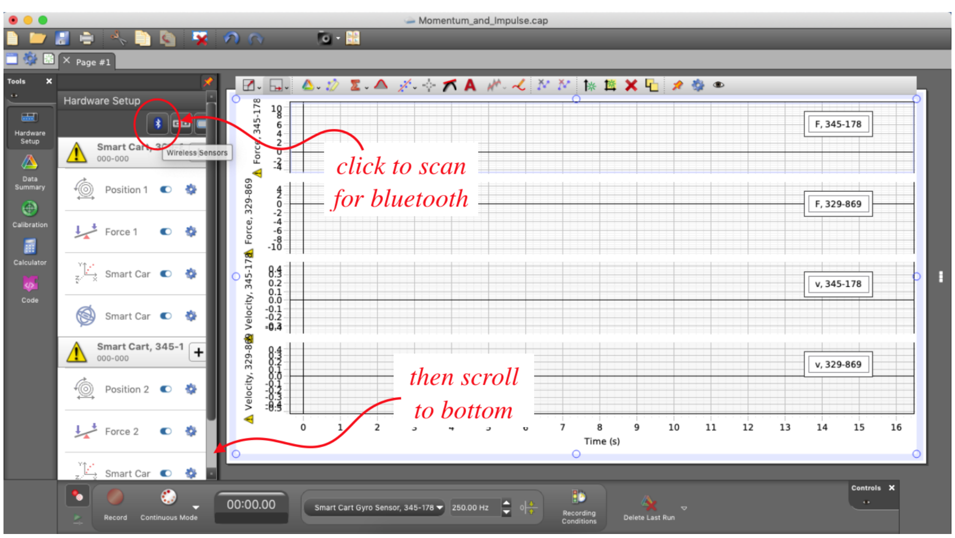
In addition to your analysis of impulse and momentum, you should also say a few words (backed-up with data!) about the conservation or non-conservation of kinetic energy in each case.

Some Things to Think About

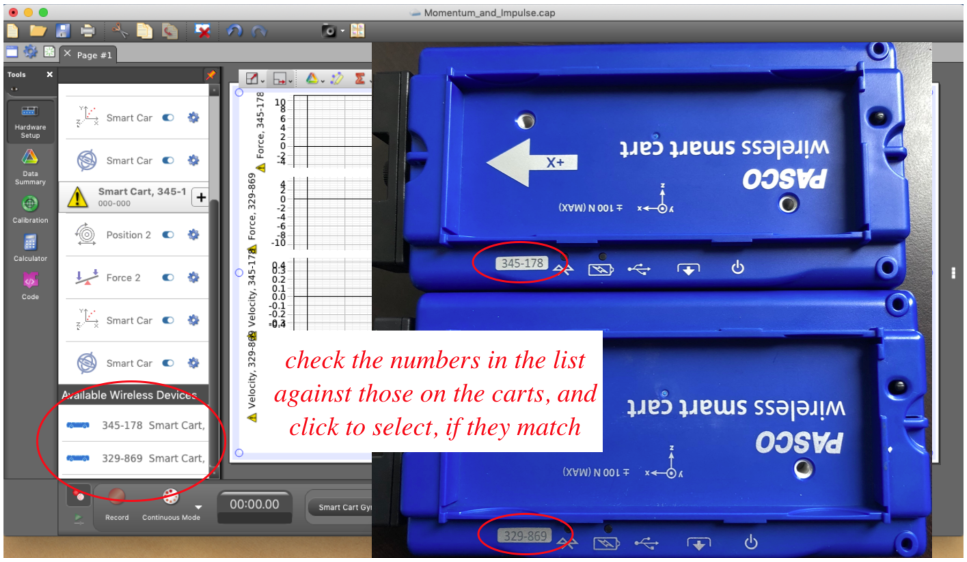
The Pasco equipment and laptop can be finicky. If you think it isn't working properly, don't waste time trying to debug it – call your TA over to assist you! Here are some things that should help, most of them related to proper use of the fancy equipment..

Here's how you get started with the equipment:

- If the carts are plugged into the laptop (they are charging), unplug them and press their power buttons. A red light should come on near the battery icon, and then the red light near the Bluetooth icon should start flashing.
- Go to the "Student" login in the laptop (there is no password), and open the 9A folder. Open the file "Momentum and Impulse."
- Run the application, and you will see what is shown below. Click the Bluetooth button at the top of the "Hardware Setup" window, and then scroll this window to the bottom.



- You should find carts available for Bluetooth pairing at the bottom of the "Hardware Setup" window. Check to make sure that the carts listed are the same ones you will be using by comparing their numbers, then click on those carts to pair them to the computer. They should then be listed higher in the window.



- When the time comes to do the link-up collision, you need to remove the magnets from the carts and replace them with the bottle-brush/tube links. Make sure that the brush that comes from one of the tubes pairs well with the other tube. If it does not, you can bend it slightly, **but remove the brush from both tubes completely before doing this – don't torque the brush/tube while connected to the cart, or you may break the cart**.

Some pointers while taking data:

- During the magnetic repulsion runs, do not push the incoming cart so hard that it contacts the other cart – the magnets should repel **without** an audible "clack." This will not only produce the best results, but will also avoid breaking the magnets.

- It is a good idea to set up your track so that the cart doesn't slow down or speed up very much when rolling on its own. There is going to be some effect due to friction in the wheels or from air resistance, but you should use the bubble level to make sure there is not a slant in the track affecting your results. Also, centering the carts in the track so that the sides don't drag is essential.
- The software has some useful tools for extracting data after a run, but it is also a little idiosyncratic. Here is what you need to know:
  -  is a tool that re-sizes the graphs to a scale that is easier to read.
  -  is the highlight tool. It provides a box for you to select a portion of a graph for future examination (see below).
  -  is the coordinate tool. When you click on it, you can move the cursor over a point on the graph, and it will display its exact coordinates.
  - is the area-under-the-curve tool. The value of this tool in a lab involved with computing impulse should be obvious. To use this, first use the highlight tool to drag a box around the part of a curve that you want to integrate, then click on this icon to compute the area under that segment of curve.
  - *Important! You will have 4 graphs on your computer screen, and you will want to use tools on each one, but the software has a maddening "feature." The graph into which the tool appears is the last one that was selected. This is as it should be, but the software selects the graph by mouse-over, rather than by clicking. So if you want a tool to appear in the bottom graph, you need to make sure that was the last graph that your cursor was over before clicking the tool, which requires you to navigate the cursor* ***around*** *the other graphs on its way to clicking the tool.*
- This lab doesn't include data tables, so you need some way to display your raw data. You should do this by taking screen captures of the graphs generated (after manipulating/magnifying them so they are easy to read). You can do this with command-shift-4, which gives you a cursor that you can drag into a box around the portion of the screen you wish to capture (the file will appear on the desktop). Getting this file from the desktop to where you can add it to your lab report is up to you. In order to do anything over a network (such as emailing the file to yourself or using Airdrop), you will need to log the lab laptop into eduroam under your login. You might also be able to take a photo of the computer screen.
- We will not be doing rigorous uncertainty analysis here (the uncertainties inherent to our black-box-measuring-apparatus are not immediately apparent), but some reckoning of how far off the results are from what you predict (oh, btw, you should be hypothesizing results in each case!) is expected. As with most experiments we do, if you are off by more than 10%, you should probably assume you made an error somewhere. Either you made an incorrect hypothesis, or something went wrong in your analysis of the data.
- When you are finished with the equipment, please power-down the carts and plug them into the laptops with their USB cords, so that they are charged for the next lab.

Lab Report

Craft a lab report for these activities and analysis, making sure to include every contributing group member's name on the front page. You are ***strongly encouraged*** to refer back to the Read Me as you do this, to make sure that you are not leaving out anything important. You should also feel free to get feedback from your lab TA whenever you find that your group requires clarification or is at an impasse.

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CHAPTER OVERVIEW

Lab 7: Navigating the Conservation Laws

7.1: Background Material

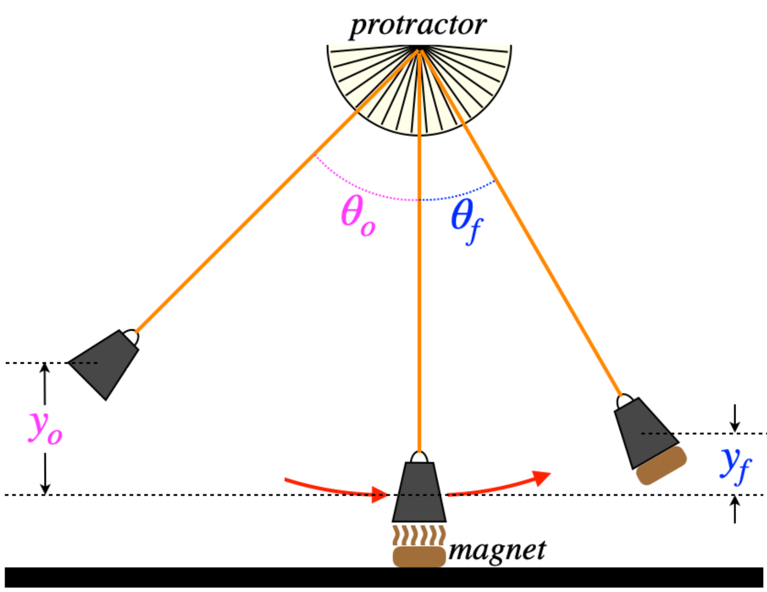
Text References

- ballistic pendulum

Tarzan & Jane

The old legend of Tarzan of the Apes evokes the classic scene where Tarzan swings down from the trees on a vine to the ground, where is grabs his girlfriend Jane, and together they swing up to another branch (perhaps he rescues her from a dangerous animal or something). There is quite a lot of physics in a process like this, and in the lab that follows, we will examine it. We don't have Tarzan & Jane action figures to simulate this process in lab, so instead we'll swing an iron weight that picks up a magnet from the tabletop. The process looks something like this:

Figure 7.1.1 – The Physical Process



While it is easier to tie energy conservation to the physical situation using the heights y_o and y_f, it is easier to measure the angles θ_o and θ_f in the lab. So as preparation for this lab, you will need to do the geometry so that you are able to translate between these two sets of coordinates. Assume that you know the length of the pendulum (which you can obviously measure in the lab).

Conservation Laws

The text reference on the ballistic pendulum is extremely helpful here. You should not be just copying-down equations from that example (because this is a different case), but rather make a note of what points during this process each conservation law (either momentum or energy) can be used, and why only that conservation law could be used in that situation. These general principles will guide you for this case as well.

Important Preparation

The starting and initial heights are clearly related to each other. For example, when the initial height is greater, the final height is also greater. When it comes to expressing the relationship between these heights mathematically, we have (as already mentioned) the conservation laws. But the number of physical parameters from which this mathematical relationship is built (especially if friction is ignored) is two – the masses of the iron weight (M) and magnet (m). It should therefore be clear what needs to be done in preparation for this lab, no matter what its ultimate goal might be: Determine the mathematical relationship between y_o, y_f, M, and m.

7.2: Activities

Equipment

- swing protractor
- pendulum support assembly
- pendulum (iron weight with string)
- magnet
- triple-beam balance

The General Idea

As described in the Background Material, we will be looking at a physical process where mass swinging on a string picks up a stationary mass. We can measure the starting height of the swinging mass and the final height of the combined mass (both indirectly with the help of a protractor). We will use those measurements for the following specific task: You will measure the mass of the swinging weight (it is ostensibly a 20 gram weight, but you may want to check that with the balance provided), and will use your measurements to compute the mass of the magnet.

A single swing will give an answer to this question, but as everyone knows, such an approach is fraught with danger regarding uncertainties. So instead, you will do many runs (at least 6, but more is better) and make a plot of y_f (the final height) vs. y_o (the starting height). If you have worked out the mathematical relationship between these heights and the masses of the two objects involved, then it should be clear how this plot will be useful for attaining your goal.

Some Things to Think About

Here are several suggestions and warnings to help you on your way:

- As usual, you should use video recording to make your measurements of the moving object as accurate as possible.
- Something we have not encountered yet in laboratory procedure turns out to be very important in this lab. It is called *calibration of the equipment*. In this lab, it comes up in two places. First, the orientation of protractor is adjustable, and you should make sure that it is positioned correctly before taking data. And second, you may find that there is a measurable friction effect between the string and the rod that supports it. You can measure this approximate amount of this effect by doing one or more runs of the pendulum drop *without* it grabbing the magnet. If there was negligible friction, then the starting and final angles of the swing would be equal. If these are not equal, then you can account for the role of friction in your actual data runs by adjusting the angle measurements according to what you learned in these calibration runs.
- Something we encountered in previous labs also comes up here. We are mapping the motion of the pendulum with the protractor behind it, so we need to minimize the effect of parallax in our view. This is accomplished in the usual ways – keep the pendulum as close to the protractor as possible, and the camera as far away as possible (while still being able to see the result).
- While the protractor is helpful (and easier to use than measuring the heights directly), it can be misused. The act of grabbing the magnet causes the iron weight to not move so "smoothly" on the string as the swing continues. This causes the string's shape to fluctuate rapidly, and it may not be reliable to use it as a way of measuring the angle. But no matter how much the *string* jitters about, the angle made by the center of mass st the end of the string is what matters here. Keep this in mind when logging data from your video recordings.
- As with previous labs that involve extracting an answer from graphical methods, we will not be determining the uncertainty range for the final answer. If you are not getting an answer within 5% of the actual mass of the magnet (you can measure this on the scale only *after* you have computed it!), then you have likely made one or more fixable mistakes.
- As usual, for your plots you should use the usual online graphing calculator to plot your data points. Now that you have done a few of these "by hand," it's time to unleash the power of our computers. Here is how to get the best-fit line (a process called *linear regression*) on Desmos: Create the data table by clicking on the "+" in the upper-left corner, and selecting "table." You will see that the variables "x_1" and "y_1" are used in the table. In the next box, put in the equation for a line with these two variables, but instead of using an equal sign, use "~". So it should look like "$y_1 \sim mx_1 + b$". A best-fit line will be drawn for you, and the values of m and b for this line will be displayed. The r^2 value is an indication of the quality of the fit, with a value of 1.0 being "perfect" (all the points lie on the line).

Lab Report

Craft a lab report for these activities and analysis, making sure to include every contributing group member's name on the front page. You are ***strongly encouraged*** to refer back to the Read Me as you do this, to make sure that you are not leaving out anything important. You should also feel free to get feedback from your lab TA whenever you find that your group requires clarification or is at an impasse.

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CHAPTER OVERVIEW

Lab 8: Rotational Dynamics

8.1: Background Material

Text References

- moment of inertia of common geometries
- unwinding spools

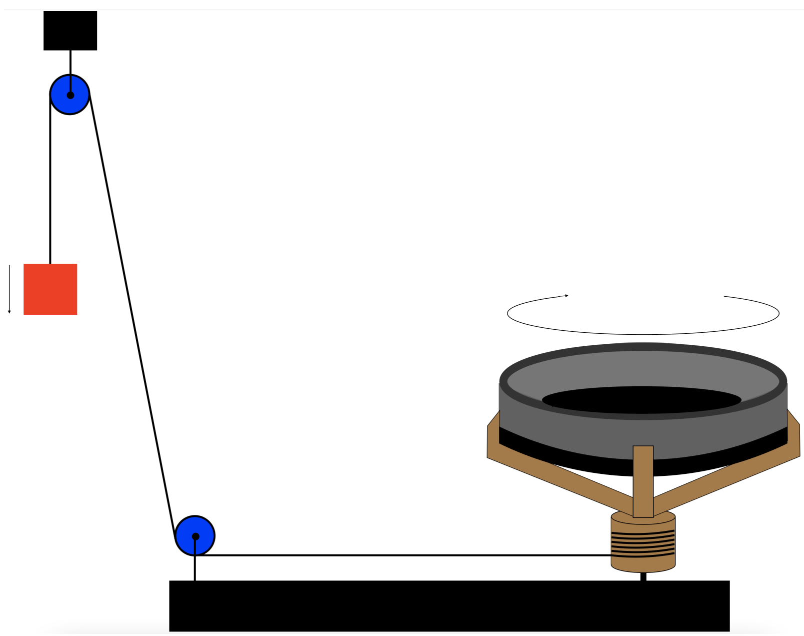
Measuring Moment of Inertia Dynamically

Half of this lab consists of using dynamics to determine the moment of inertia of a thick circular ring. The first thing that should come to mind when thinking of "dynamics" and "inertia" is Newton's second law. In this case, it is the version of the second law that applies to rotations:

$$\vec{\alpha} = \frac{\tau_{net}}{I} \tag{8.1.1}$$

Clearly if we can measure the torque and angular acceleration, we immediately have the value of the moment of inertia. But these are not the easiest values to measure directly, so we have an experimental setup that simplifies the task somewhat:

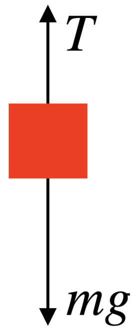
Figure 8.1.1 – Experimental Apparatus

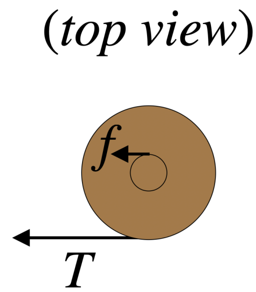


As the mass accelerates downward, it accelerates the ring in the cradle in a rotational fashion. Their motions are linked by the fact that the string does not slip as it unwinds from the hub, and we can pretty easily measure the acceleration of the descending block. As for the torque on the rotating system, we can get this from the tension that pulls on the hub (minus a small contribution by friction on the hub by the axle), and the radius of the hub. With the tension also affecting the motion of the mass, we end up with a convenient result.

Let's solve the physics problem. Start with free-body diagrams. For the hub, we will take a top view, and since we are only interested in the torques, we will leave off the balancing force on the hub by the axle that acts through its center.

Figure 8.1.2 – Free-Body Diagrams





As the mass descends, the hub rotates clockwise according to the diagram. Summing the forces on the block and the torques (about the axle) on the hub, we get two second-law equations (f is the frictional force on the hub by the axle, N is the normal force on the hub by the axle, R is the radius of the hub, r the radius of the axle, and I is the moment of inertia of the rotating system):

$$F_{net} = mg - T = ma \qquad \tau_{net} = TR - fr = I\alpha \tag{8.1.2}$$

The "string unwinds without slipping" constraint gives a relation between the linear acceleration of the mass and the rotational acceleration of the ring & cradle:

$$a = R\alpha \tag{8.1.3}$$

Putting these three equations together such that we eliminate α and T (neither of which is easy to directly measure in an experiment), we get the following equation:

$$a = \frac{mR^2}{I}(g - a) - \frac{fRr}{I} \tag{8.1.4}$$

It might seem odd that we left the acceleration a on both sides of this equation, but there is a reason for this. When you actually perform this experiment, you will find that the acceleration a is much, *much* less than g (on the order of 0.1% of g for the weights we will hang on the string), so we should feel fairly comfortable ignoring entirely the second term on the right side of that equation. This gives us an equation for a line with two measurable quantities, a and m, as variables:

$$a = \left(\frac{gR^2}{I}\right) m - \frac{fRr}{I} \tag{8.1.5}$$

Conveniently, the moment of inertia of the rotating platform appears as a factor in the slope of that line. We don't know the friction force or the radius of the axle, so we can't really deal with the second term (nor do we need to), but it is a negative constant, which means that if we plot a vs. m, we would expect the y-intercept to be below the horizontal axis (i.e. this is not one of those cases where we can use the origin as an extra data point). [*Note: It is common to express the slope of a line as "m", as in "$y = mx + b$". In the linear equation above, the variable m represents the mass hung from the string, and it is actually the "x" in the linear equation. The slope of this line is the constant in parentheses.*]

8.2: Activities

Equipment

- rotating cradle + metal disk, with string around hub
- iron ring
- pulley assembly
- hanging weights
- digital scale
- 2-meter stick
- vernier calipers

The General Idea

As we did in Lab #4 with static friction, we will be measuring a physical quantity using two very different methods, and then compare the two results, looking for confirmation. In this case, the quantity we will be measuring is the moment of inertia of a heavy iron ring. One way that we will measure its moment of inertia is dynamically, as detailed in the Background Material. The second method is up to you, but it will not involve the rotating cradle apparatus. You are of course free to measure any aspect of the ring's physical features that you wish, and you can use whatever formulas you can find in the textbook.

Some Things to Think About

This lab incorporates many things you have done before, so the direction you are given is intentionally pretty scant. Still, when it comes to the dynamic measurement, here are a few things to keep in mind:

- ***Important! – For the turntable to work properly, the string must wrap around the hub. This is only assured when there is tension in the string. If the string goes slack while the turntable is rotating, the string will wrap around the axle rather than the hub, and there's a good chance this will render the turntable inoperable.***
- You have some already computed accelerations of objects dropped from rest (Lab #3 on air resistance), so you should draw on that experience in this lab. One suggestion for a change from that procedure is that the start of the timer can be easily be synchronized with the release of the rotating platform if both tasks are performed by the same person.
- Upon reading the Background Material, you undoubtedly figured out that there is a best-fit line (actually, two) in your future. Go ahead and use the online calculator for this.
- When you find the moment of inertia dynamically, you have calculated it for the *object that is rotating*. In this case, what is rotating is *not* just the iron ring – the metal disk under the ring and cradle itself are also involved. How will you account for this? The additive property of moments of inertia around a common axis seems like it will be useful, but don't assume there is a quick-fix – a separate experiment may be needed.
- If you are unfamiliar with how to make measurements with the vernier calipers, ask your TA for assistance.
- Use great care when handling the iron ring to weigh it. If it rolls off the scale, it can do a great deal of damage to someone's foot.
- Keep in mind that you want the weight to drop far enough to keep the percentage uncertainties in distance and time quite small (say, below 1%), while not allowing the platform to get spinning very fast (which brings in air resistance error). This will require a judicious choice of your range of hanging weights. Note that if/when you do two separate experiments, you do not need to use the same range of weights for both.
- Of the two methods of computing the moment of inertia, the dynamic one carries by far the most uncertainty. As (in this class) we do not deal with uncertainty of values we find graphically, uncertainty computations will not be part of this lab. Meticulous care in taking data is still paramount, however, and this should allow you to reach agreement between the two measurements that is within 5%. If the disparity is more than this, but less than 10%, then that is probably because the data could have been gathered more carefully. If the disparity is more than 10%, then you almost certainly made a critical error or omission somewhere.

Lab Report

Craft a lab report for these activities and analysis, making sure to include every contributing group member's name on the front page. You are ***strongly encouraged*** to refer back to the Read Me as you do this, to make sure that you are not leaving out anything

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CHAPTER OVERVIEW

Lab 9: Static Equilibrium

9.1: Background Material

Text References

- solving static equilibrium problems

Not Much Else!

This lab is pretty much a real-world static equilibrium problem. If you understand how to do this process (starting with the free-body diagram, and including things like choosing a pivot, determining moment-arms, etc.), then you are ready to go!

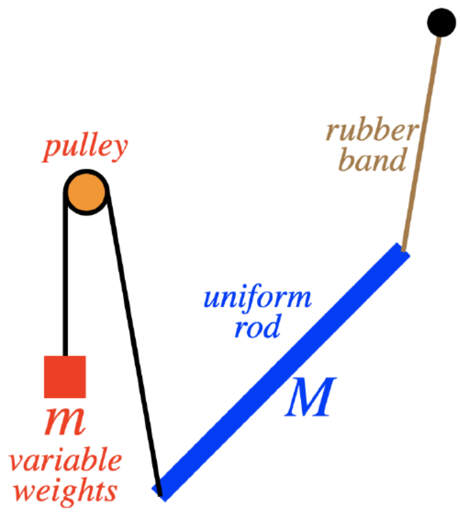
9.2: Activities

Equipment

- aluminum bar
- support assemblies, one with a pulley
- hanging weights & string
- rubber band
- paperclips
- plumb-bob
- ruler
- goniometer (adjustable protractor)

The General Idea

We will use methods of solving static equilibrium problems to indirectly measure forces present in a system of stationary objects. The system in question looks like this:



The lab consists of two parts:

1. You are allowed to adjust the amount of variable weight however you see fit. With this power, and armed *only* with a plumb-bob, determine the mass of the uniform rod. You should also vary the weights by very small amounts (amounts that don't change the system's state a noticeable amount) as a means of determining the uncertainty in your answer.
2. Reassemble the system with an amount of hanging weight that is *substantially different* from the weight you used in part 1. Then, armed with only a plumb-bob and a goniometer, do the following:
   - Re-compute the mass of the rod using this setup. Confirm that the value you compute falls within the boundaries of uncertainty of the answer you got in part 1.
   - Compute the force exerted on the rod by the rubber band. Devise a way to check your answer another way that doesn't involve static equilibrium methods (you may disassemble the system). There is no uncertainty check for this part of the lab, but you should compute by what percentage the two answers differ (if it is more than 5%, you have almost certainly made an error, as you should be able to get close to 1%).

Some Things to Think About

This lab is very straightforward in its statement, so there is not a lot to say about it, but here are a couple of things that you should know already:

- If you are not drawing free-body diagrams, choosing a coordinate system and a pivot point, breaking forces into components – basically treating this like a physics homework problem – then you are missing the point entirely.

- Make sure you are measuring angles properly with the goniometer – the vertex of the angle has to coincide with the goniometer's pivot, and the two lines that form the angle lie along the central lines in the arms of the goniometer.

Lab Report

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